HIGGS PROPERTIES: SPIN, PARITY AND COUPLINGS

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1

AFTER DISCOVERY:

WHAT'S NEXT IN HIGGS PHYSICS?

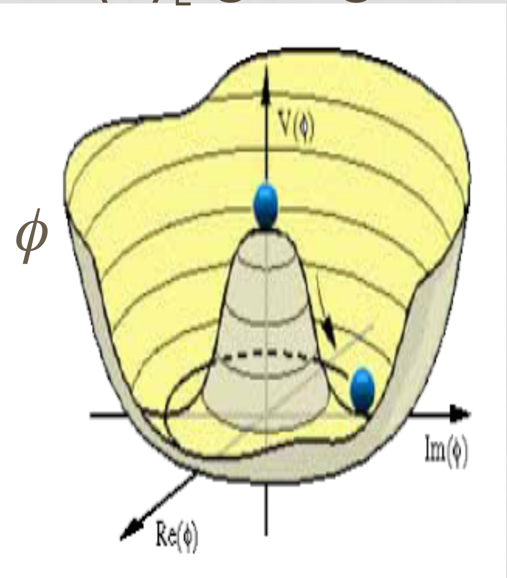
1 OCTOBER, 2012, BROOKHAVEN NATIONAL LABORATORY

ELECTROWEAK SYMMETRY BREAKING

Problem #1: W and Z boson masses violate $SU(2)_L$ gauge invariance

Solution: Postulate #1

There exists a scalar complex field *doublet* ϕ



- Mexican hat (bottle's bottom) potential

$$V(\phi) = \lambda(-v^2\phi^*\phi + (\phi^*\phi)^2)$$

- Minimum at $\phi_{\min} = v/\sqrt{2}$
- Non-zero v generates masses for W and Z-bosons
  - Absorb 3/ 4 degrees of freedom
  - Given W mass (muon decay rate) v is constrained to be 246 GeV
  - Predict ratio between W and Z masses - verified in experiment
- One remaining d.o.f. – Higgs boson (s=0, P=+)

HIGGS BOSON

- Expand ϕ near its minimum $\phi = [v + h(x)] / \sqrt{2}$
- Lagrangian

$$L = \frac{1}{2}[(\partial^{\mu} - igA_{\mu})(v+h)(\partial^{\mu} + igA_{\mu})(v+h)] +$$

$$+ \frac{1}{2}\mu^2 (v+h)^2 - \frac{1}{4}\lambda(v+h)^4 - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

- ***$(g^2v^2/2)A_{\mu}A^{\mu}$*** – mass term for gauge bosons
- ***λv^2h^2*** – mass term for the scalar boson itself
- ***h^3, h^4*** **–**self interaction terms
- ***hAA, h^2AA*** – interaction with gauge fields terms

v constrained by M_W

λ- free parameter

Higgs mass is not predicted

This is what we were after

Byproducts

Strength of these terms is predicted given λ (M_H)

HIGGS MECHANISM OF FERMION MASS GENERATION

Problem #2: fermion masses violate $SU(2)_L$ gauge invariance

Solution: Postulate #2

- Yukawa-like coupling to fermions – generate fermion masses in a gauge invariant way through interaction with Higgs field
- This mechanism does not reduce the number of free parameters in the model, masses are traded for the strength of interaction with the Higgs field (g_f)

$$\sqrt{\frac{1}{2}} g_f v(\bar{f}_L f_R + \bar{f}_R f_L) \qquad\qquad m_f = \sqrt{\frac{1}{2}} g_f v$$

TESTABLE PREDICTIONS

- Existence of a true scalar boson – measure spin, parity
- Couplings to gauge bosons
  - Probing custodial symmetry – one of best motivated symmetries given that the new state is responsible for breaking the EW symmetry
- Coupling to fermions
    - New state can be responsible for EW symmetry breaking but **NOT** for generation of fermionic masses – fermiophobic Higgs
- Self coupling
  - ***h^3,h^4* –**self interaction terms arise from the same assumption as couplings to gauge fields. Interesting to test their absolute and relative strength
  - Require large statistics to observe

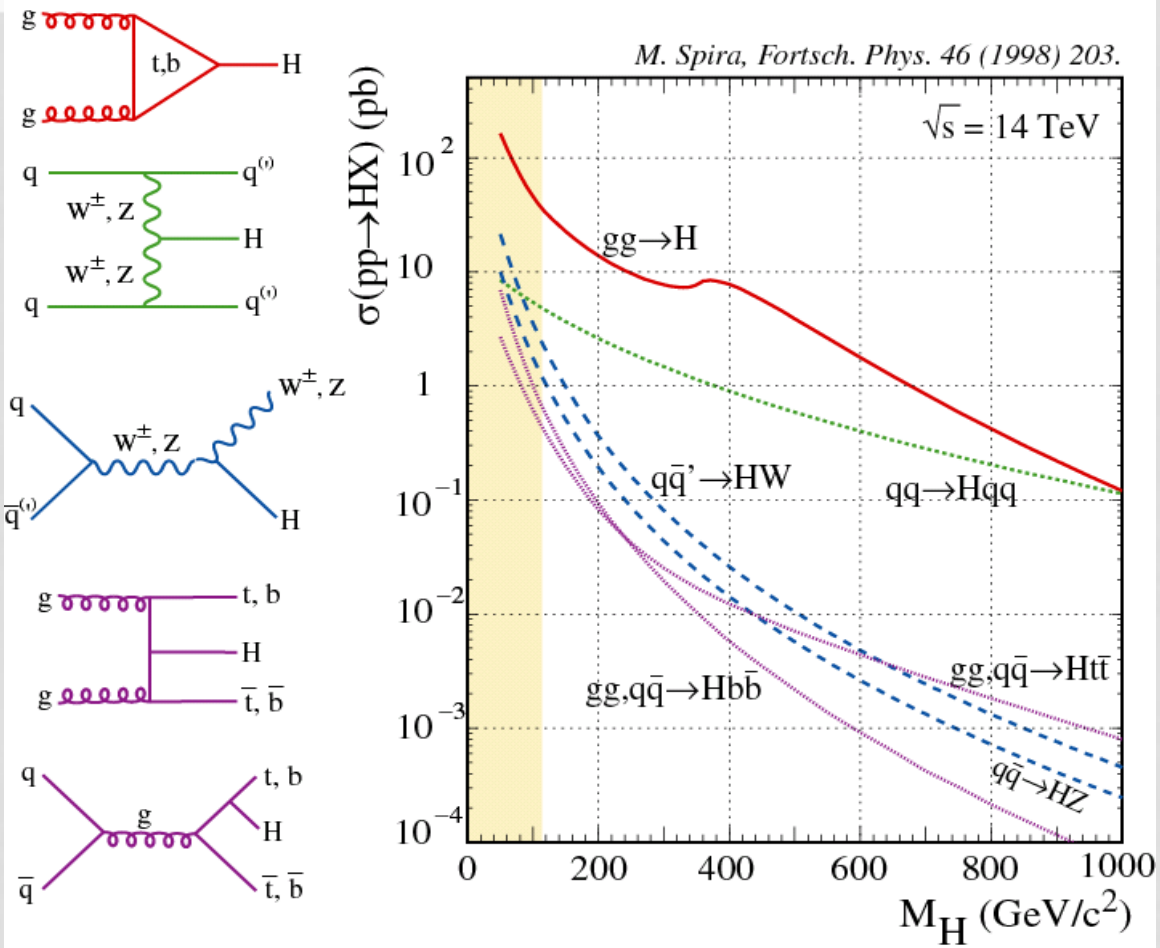
HIGGS PRODUCTION @ LHC

Gluon Fusion
- dominant process

Vector Boson Fusion
20% of gg @ 120GeV

Associated Production
W or Z (1-10% of gg)

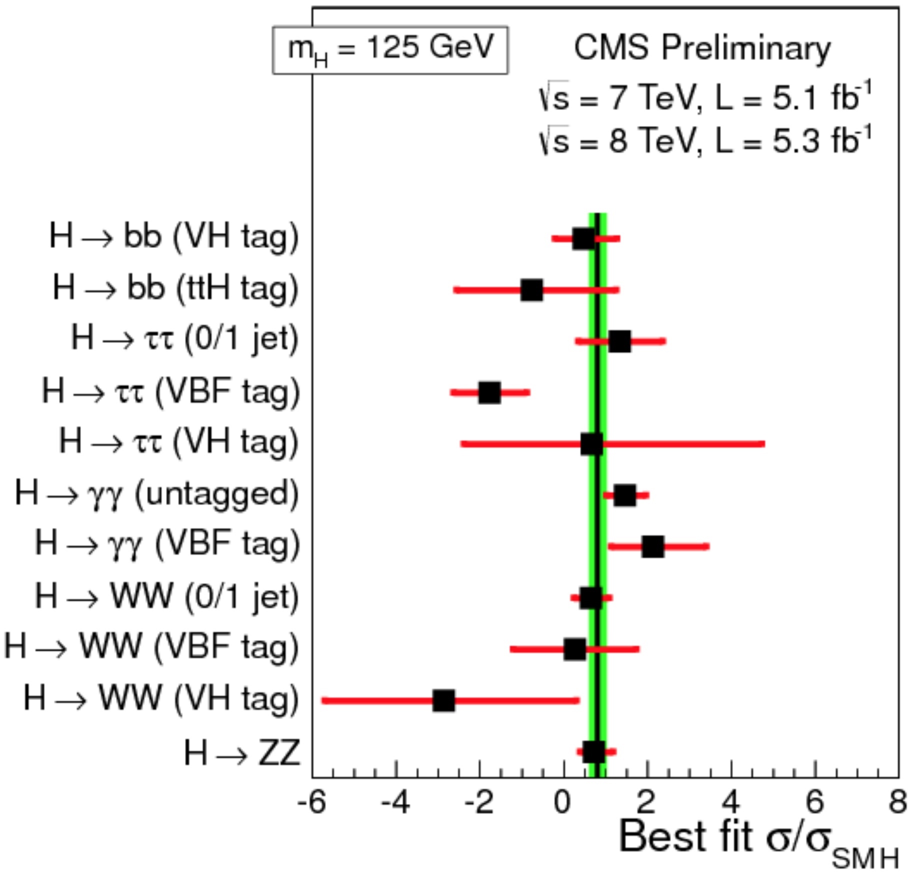
Associated Production
ttbar or bbbar (1-5% of gg)



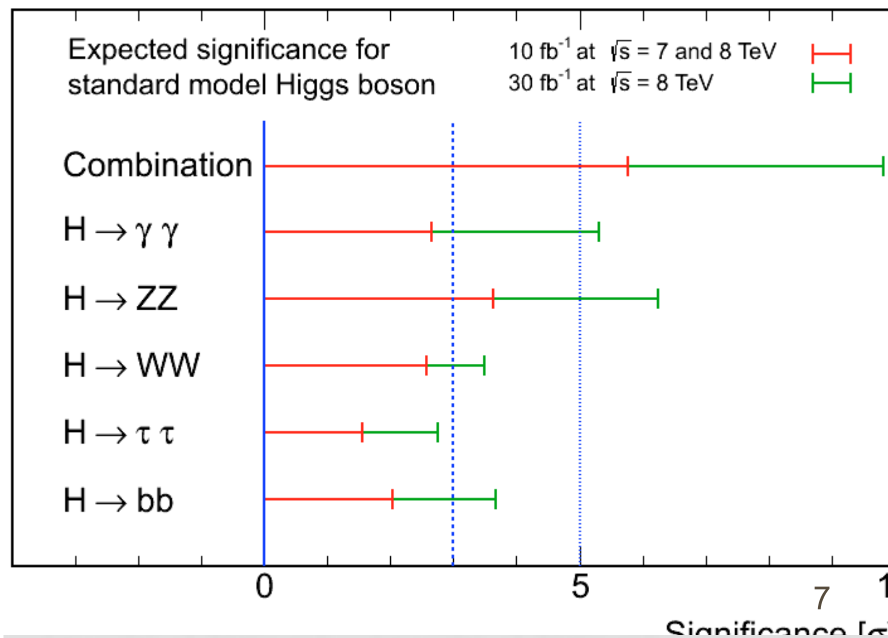
4 production mechanism ➡ key to measure H-boson parameters

PROJECTED SIGNAL

Current status: signal observed in ZZ, γγ and WW modes
There is some evidence (Tevatron) for bbbar coupling

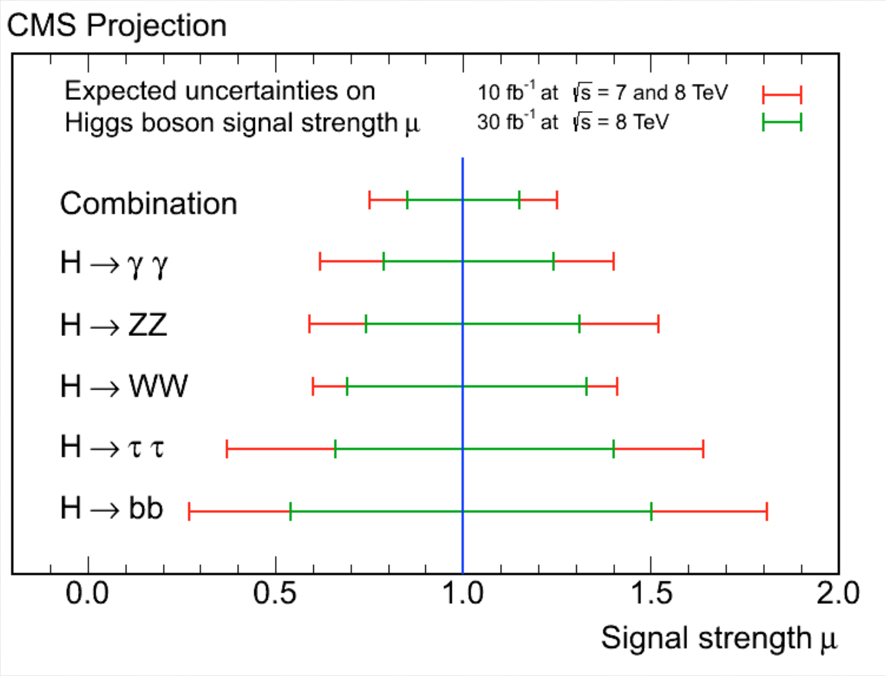


Projected signal by the end of the run

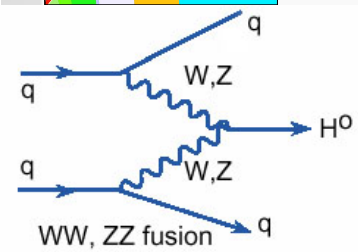


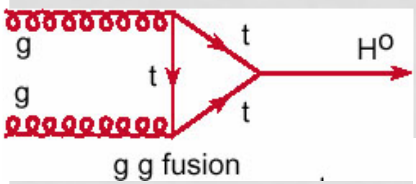
OBSERVABLES

- the framework to probe the Higgs couplings issued by the "low mass" LHCXS WG and endorsed by both CMS and ATLAS: arXiv: 1209.0040
- Overall signal strength μ



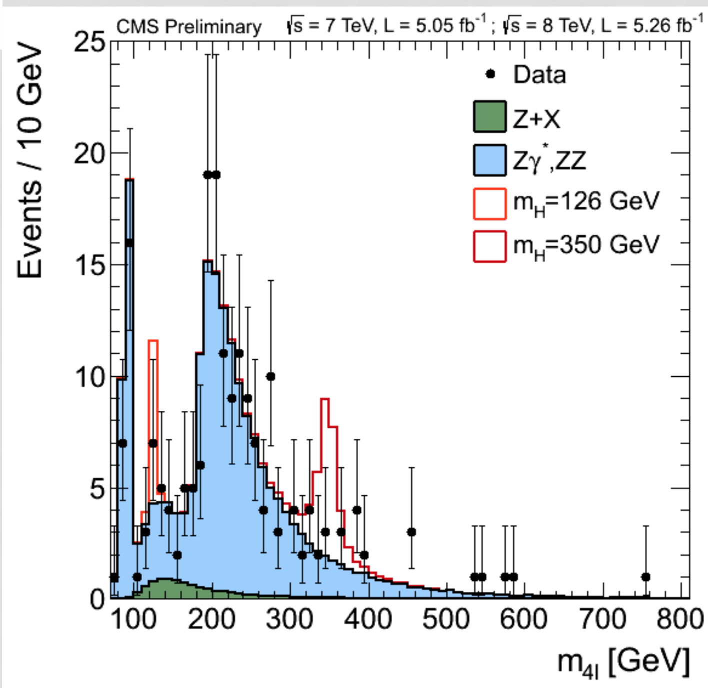
DISENTANGLING COUPLING FROM PRODUCTION AND DECAY

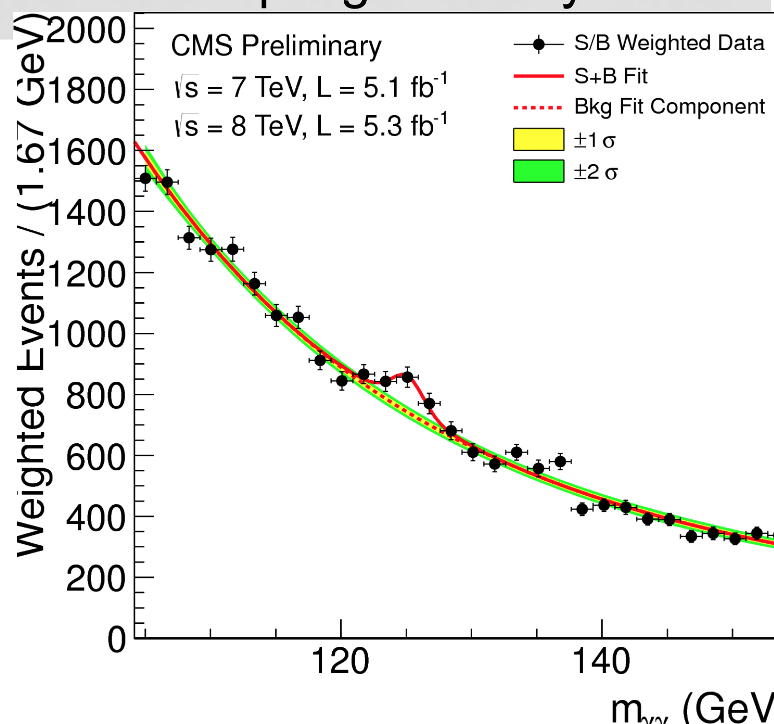




VBF production – sensitive to vector boson couplings
gg→H – sensitive to quark loops;

H→γγ – fermion+W loop
H→WW, ZZ – vector boson coupling at decay





DISENTANGLING COUPLING FROM PRODUCTION AND DECAY

Boson and fermion scaling assuming no invisible or undetectable widths

Free parameters: $\kappa_V (= \kappa_W = \kappa_Z)$, $\kappa_f (= \kappa_t = \kappa_b = \kappa_\tau)$.

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH, $t\bar{t}H$	$\frac{\kappa_f^2 \cdot \kappa_\gamma^2(\kappa_f,\kappa_f,\kappa_f,\kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_f^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_f^2 \cdot \kappa_f^2}{\kappa_H^2(\kappa_i)}$	
VBF, WH, ZH	$\frac{\kappa_V^2 \cdot \kappa_\gamma^2(\kappa_f,\kappa_f,\kappa_f,\kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_V^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_V^2 \cdot \kappa_f^2}{\kappa_H^2(\kappa_i)}$	

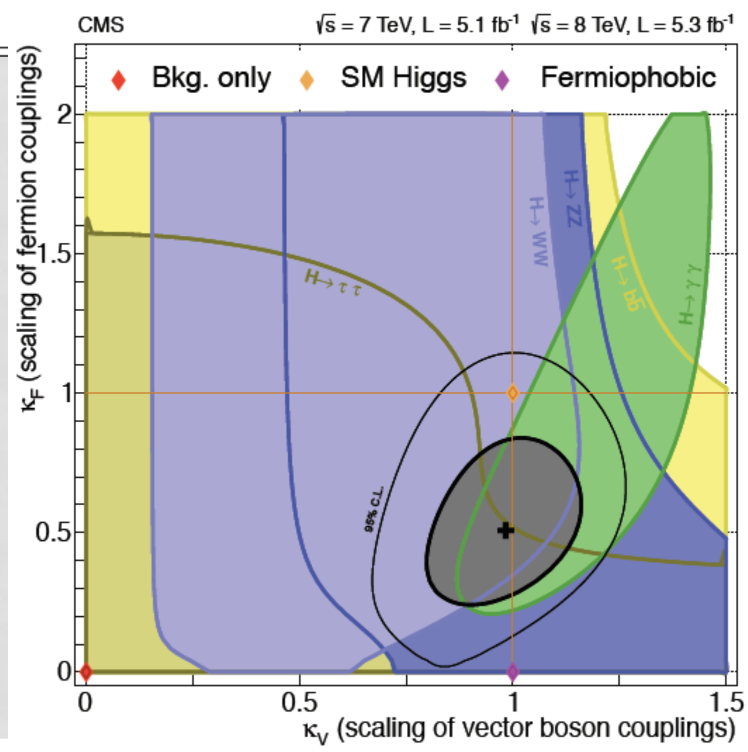
$k_V k_F$ - scale vector and fermion coupling

$K_\gamma(k_V, k_F)$ – coupling to γ, depends on W and fermion loops ($H \to \gamma\gamma$)

$gg \to H$ – sensitive to quark loops;

$H \to WW$, ZZ – vector boson coupling

No direct Higgs to fermion couplings observed yet, limits on $H \to \tau\tau$, $H \to bb$



CURRENT STATUS: TESTING CUSTODIAL SYMMETRY

- λ_{WZ}: ratio of scale factors for W and Z

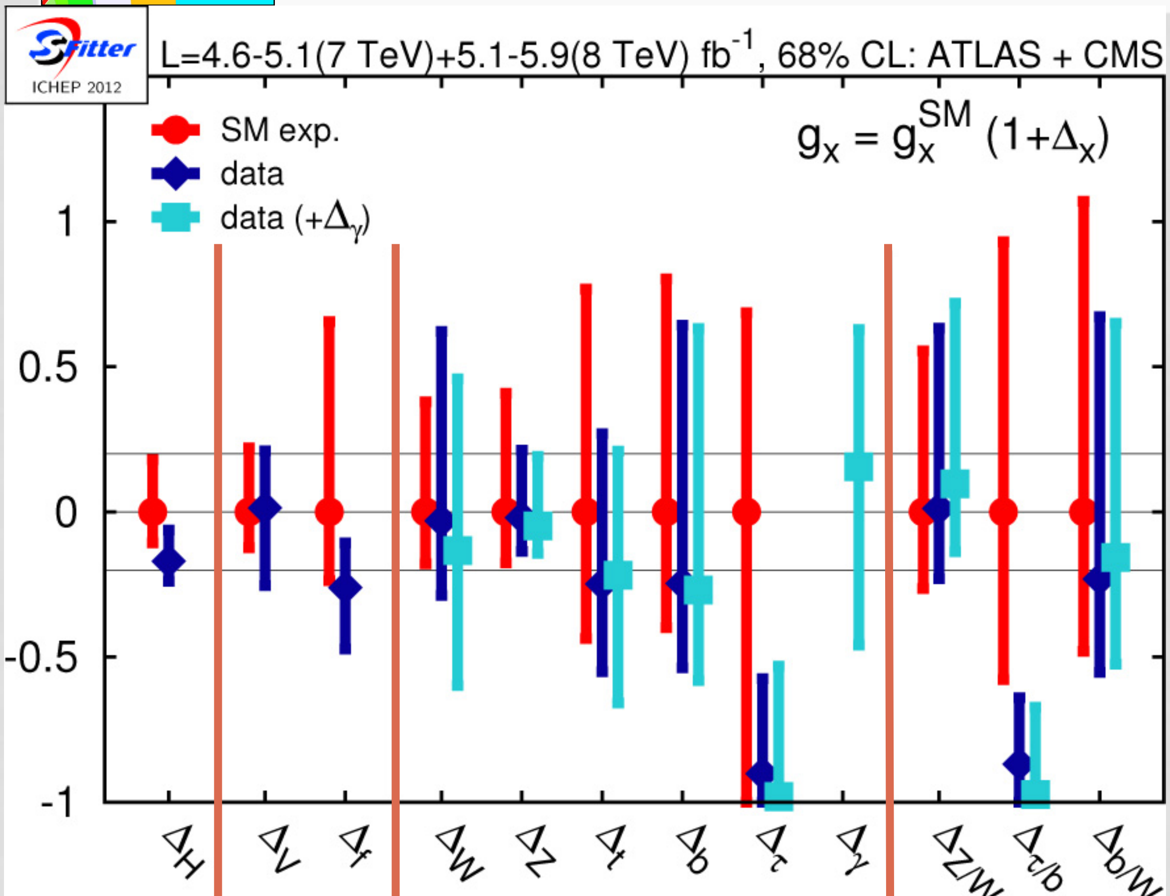
- The measurement of the H→WW/H→ZZ ratio is mostly driven by the ratio of the Higgs couplings to WW and ZZ, which is protected by custodial symmetry
- Combination of “inclusive” WW and ZZ yields gives

$R_{WW/ZZ}=0.9^{+1.1}_{-0.6}$

MORE TESTS TO COME

- λ_{lq}: ratio of scale factors for leptons and quarks
  - kV left floating in the fit
- λ_{du}: ratio of scale factors for down and up type of fermions
  - kV left floating in the fit
- κ_g- κ_γ: contour of loop scale factors
- $BR_{Inv,Undet}$: same as κ_g- κ_γ but with a scale factor in the total width accounting for invisible or undetectable decay modes

SFITTER COMBINATION ARXIV:1207.6108



I II III IV

$$g_{xxH} \equiv g_x = (1 + \Delta_x)\ g_x^{\mathrm{SM}}$$

$$\frac{g_{xxH}}{g_{yyH}} \equiv \frac{g_x}{g_y} = (1 + \Delta_{x/y}) \left(\frac{g_x}{g_y}\right)^{\mathrm{SM}}.$$

I – vary overall signal strength;
II – independent vector boson and fermion couplings
III – independent W, Z, t,b,τ and γ couplings
IV – vary coupling ratios

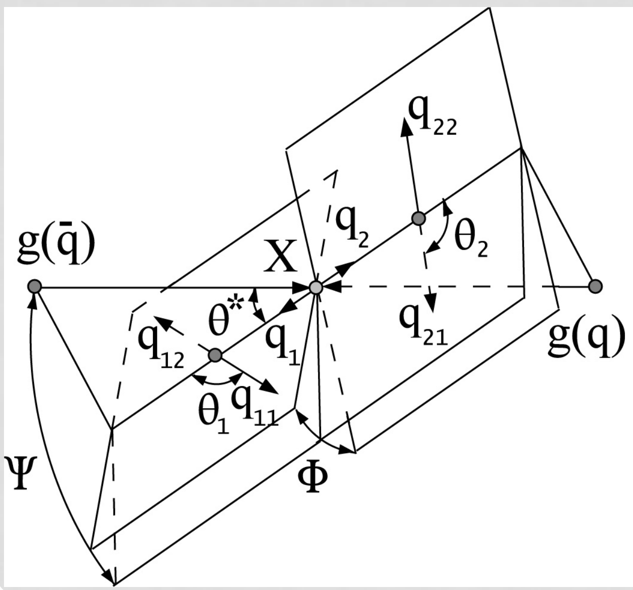
SPIN MEASUREMENT

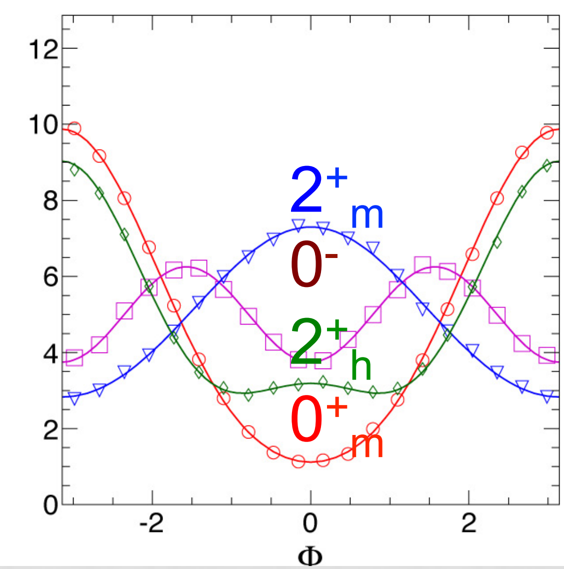
ARXIV:1208.4018

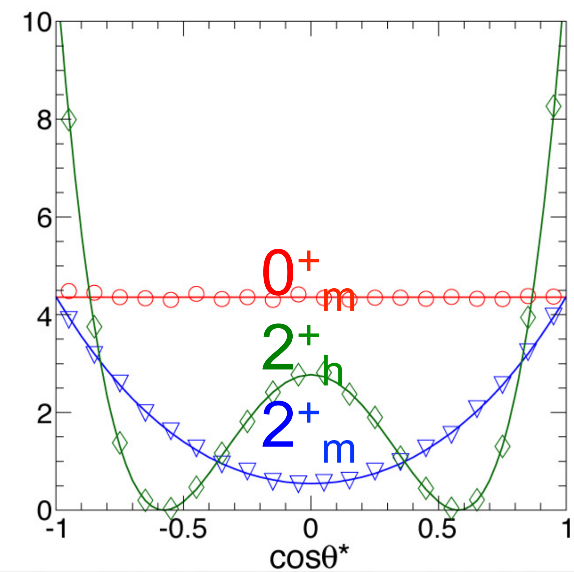
- X→γγ excludes s=1 option (Landau-1948, Yang -1950)
- X→ZZ→4l system is described by 5 non-trivial angles

Different scenarios result in distinct angular distributions

scenario	comments
0_m^+	SM Higgs boson scalar
0_h^+	scalar with higher-dimension operators
0^-	pseudo-scalar
1^+	exotic pseudo-vector
1^-	exotic vector
2_m^+	graviton-like tensor with minimal couplings
2_h^+	tensor with higher-dimension operators
2_h^-	“pseudo-tensor”





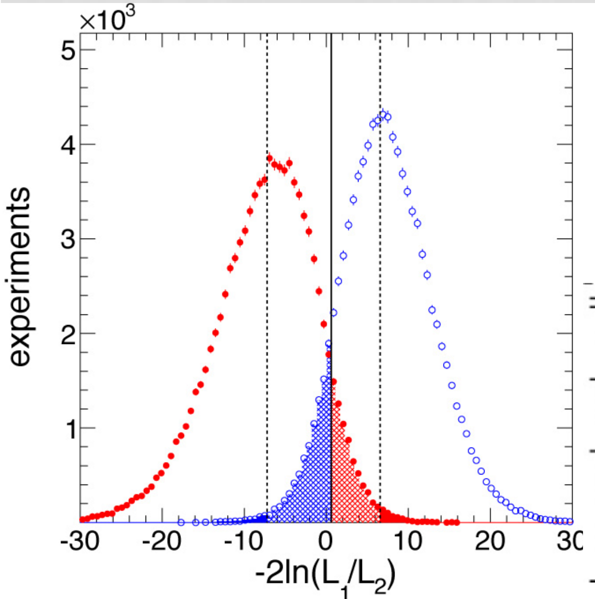


COMPARING SPIN-PARITY HYPOTHESES

- Matrix Element Likelihood Analysis (MELA) allows for optimal separation of different s^P hypotheses

X→ZZ→4l

0^+(SM) vs 0^- hypothesis

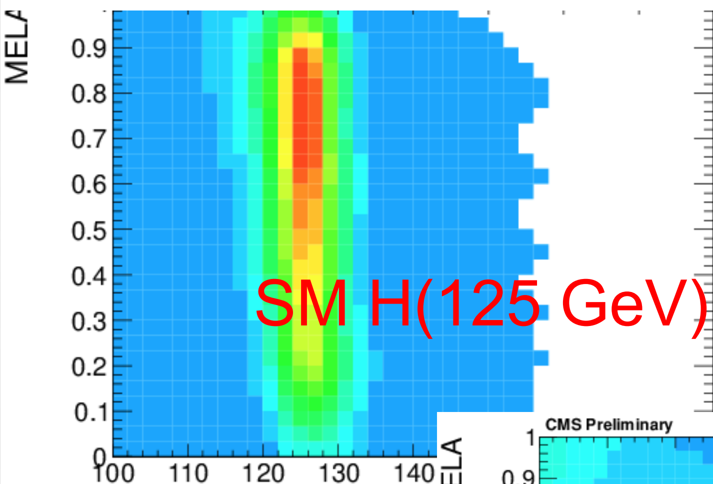


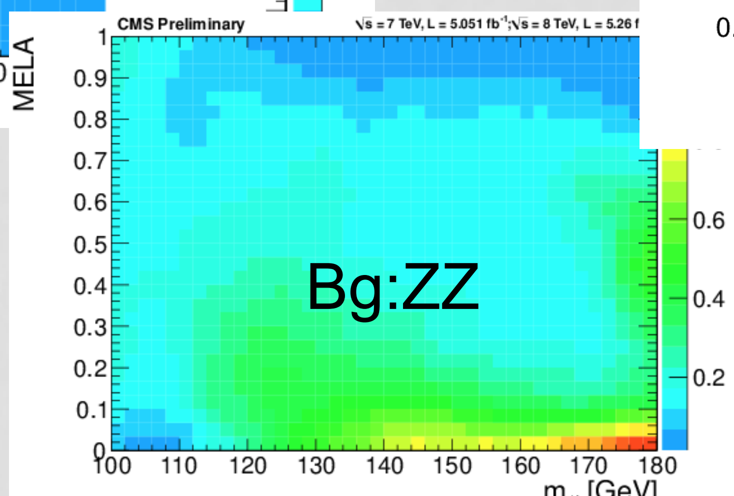
Expected significance of hypotheses separation based on 35 fb^{-1}

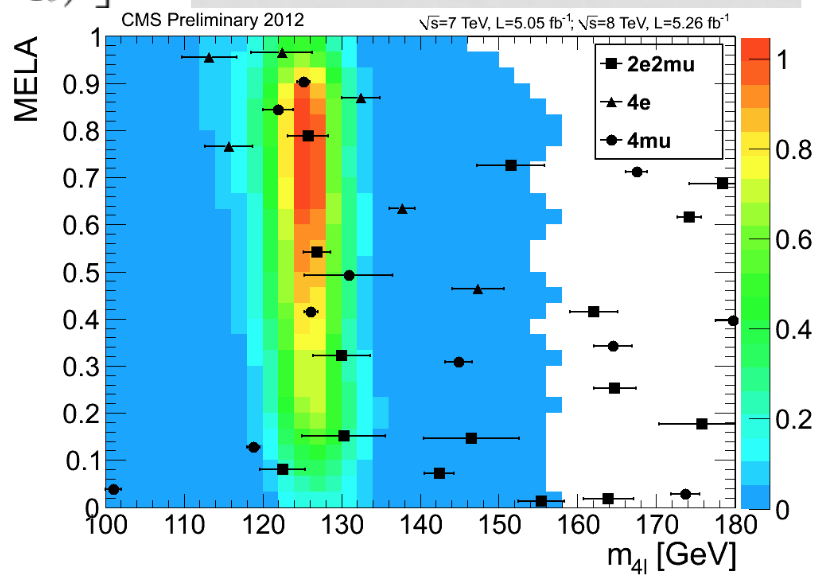
scenario	$X \to ZZ$	$X \to WW$	$X \to \gamma\gamma$	combined
0_m^+ vs background	7.1	4.5	5.2	9.9
0_m^+ vs 0^-	4.1	1.1	0.0	4.2
0_m^+ vs 2_m^+	1.6	2.5	2.5	3.9

MELA – WAS ALREADY USED TO SEPARATE SIGNAL FROM BG

$$\text{MELA} = \left[1 + \frac{\mathcal{P}_{\text{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\text{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$







Data w.r.t 126 GeV Higgs Expectation

SUMMARY

- Observed narrow resonance at 125.3+-0.6 GeV couples to weak gauge bosons and hence is potentially responsible for the EW symmetry breaking
- To verify this hypothesis it is necessary to show that its properties are consistent with the prediction:
- Spin=0, Parity =+
  - An angular based analysis is developed that has a potential to exclude pseudoscalar and tensor hypotheses based on 35 fb^{-1}
- The framework is developed to independently measure
  - Vector and fermion couplings
  - W and Z boson couplings
  - Lepton and quark couplings